



# **Sensitivity Analysis of Wind Plant Performance to Key Turbine Design Parameters: A Systems Engineering Approach**

## **Preprint**

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# Sensitivity Analysis of Wind Plant Performance to Key Turbine Design Parameters: A Systems Engineering Approach

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This paper introduces the development of a new software framework for research, design, and development of wind energy systems which is meant to 1) represent a full wind plant including all physical and nonphysical assets and associated costs up to the point of grid interconnection, 2) allow use of interchangeable models of varying fidelity for different aspects of the system, and 3) support system level multidisciplinary analyses and optimizations. This paper describes the design of the overall software capability and applies it to a global sensitivity analysis of wind turbine and plant performance and cost. The analysis was performed using three different model configurations involving different levels of fidelity, which illustrate how increasing fidelity can preserve important system interactions that build up to overall system performance and cost. Analyses were performed for a reference wind plant based on the National Renewable Energy Laboratory's 5-MW reference turbine at a mid-Atlantic offshore location within the United States. Three software configurations were used: 1) a previously published wind plant cost model using simplified parametric scaling relationships, 2) an integrated set of wind turbine and plant engineering and cost models that use a "bottom-up" approach to determine overall wind plant performance and cost metrics, and 3) the second set of models plus the addition of a plant layout and flow model for calculation of energy production. Global sensitivity analysis was performed on each analysis set with respect to key wind turbine configuration parameters including rotor diameter, rated power, hub height, and maximum tip speed. The analyses show how the latter approaches capture important coupling throughout the wind plant in a way that has not previously been achieved. In addition, while deficiencies even in the newer model set are readily identifiable, the flexibility of the new framework shows how extension and gradual buildup of model fidelity for various parts of the system provide a powerful tool that enables analysis for an ever-expanding set of wind energy research and design problems.

## Nomenclature

$AEP$	= (Net) Annual energy production
$BOS$	= Balance of station (Costs)
$COE$	= Cost of energy
$FR$	= Financing rate
$OPEX$	= Operational expenditures
$S_x$	= Sobol index main effect
$TCC$	= Turbine Capital Costs
$T_x$	= Sobol Index Total Effect
$V_{ref}$	= Reference wind speed [m/s]

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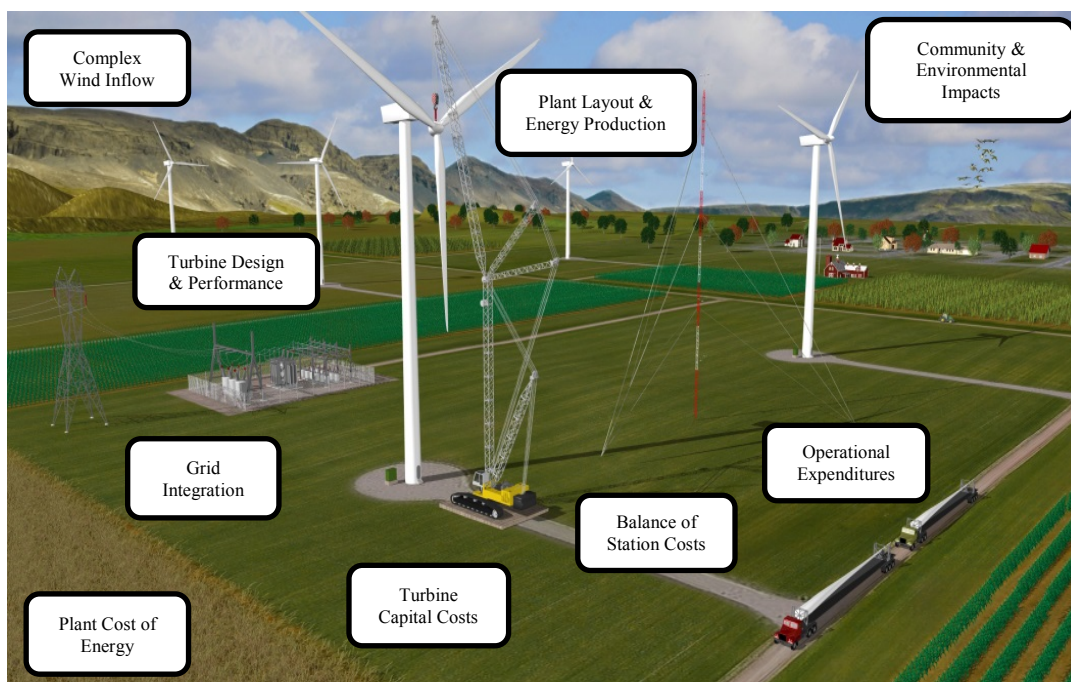
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$V_{e50}$	= 50-year extreme wind speed [m/s]
$z$	= Reference height
$z_{hub}$	= Hub height

## I. Introduction

Over the last few decades, wind energy has evolved into a large international industry involving major players in the manufacturing, construction, and utility sectors. Coinciding with industry growth, significant innovation in the technology has resulted in larger turbines and wind plants with lower associated costs of energy. However, the increasing importance of wind energy's role within the electricity sector imposes more requirements on the technology in terms of performance, reliability, and cost. To address these changing expectations, the industry has made efforts that focus on achieving a variety of goals including reducing installed capital costs for the turbine and plant, decreasing the downstream costs for operation and maintenance (O&M), increasing energy production, and minimizing negative external impacts such as noise emission or habitat disruption. In many cases, these goals involve trade-offs. For example, up-front investment in a robust component design may avoid large downstream costs for component repair and replacement. In another case, the design of a machine with a higher tip speed can reduce required torque and loads through the drivetrain, but at the same time these higher tip speeds can lead to more aerodynamic noise that adversely impacts surrounding communities. Trade-offs such as these exist throughout the entire system.

To fully assess how a change in a design parameter affects the myriad of objectives in system performance and cost, a holistic and integrated approach is needed. To address this need, the National Renewable Energy Laboratory (NREL) has embarked on an initiative to use methods of systems engineering applied to the research, design, and development of wind energy systems. Methods within the field of systems engineering, such as multidisciplinary design analysis and optimization, have been applied for many years to the engineering and design of aerospace and automotive technologies and are increasingly being applied to wind energy technology.<sup>1</sup> These methods are useful when analyzing complex "systems of systems." Wind power plants are similar systems in which components are collected into subsystems (i.e., stages of a gearbox), subsystems into even larger subsystems (i.e., the drivetrain), and into a larger complete machine (the turbine), which have interactions at higher system levels (from the plant to the electric grid). The entire wind plant is interconnected and understanding plant performance and cost is dependent on addressing the full system as illustrated in Fig. 1.



**Figure 1. Overall wind plant performance and cost.** *Design of wind energy systems depends on many variables for components, turbines, and plants; these decisions all affect ultimate performance, cost, and community impacts.*

A collaboration between the Danish Technical University (DTU) Wind Energy group and NREL aims to create Framework for Unified Systems Engineering & Design of Wind Plants (FUSED-Wind), a new software that provides a standard approach to integrating wind turbines and plants together for system analysis applications. NREL's individual effort using FUSED-Wind focuses on the implementation of a wind plant system modeling software, the Wind Integrated Systems Engineering & Design Model (WISDEM)). This software integrates several wind plant analysis software packages to 1) represent a full wind plant including all physical and nonphysical assets and associated costs up to the point of grid interconnection, 2) allow use of interchangeable models of varying fidelity for different aspects of the system, and 3) support system-level multidisciplinary analyses and optimizations.

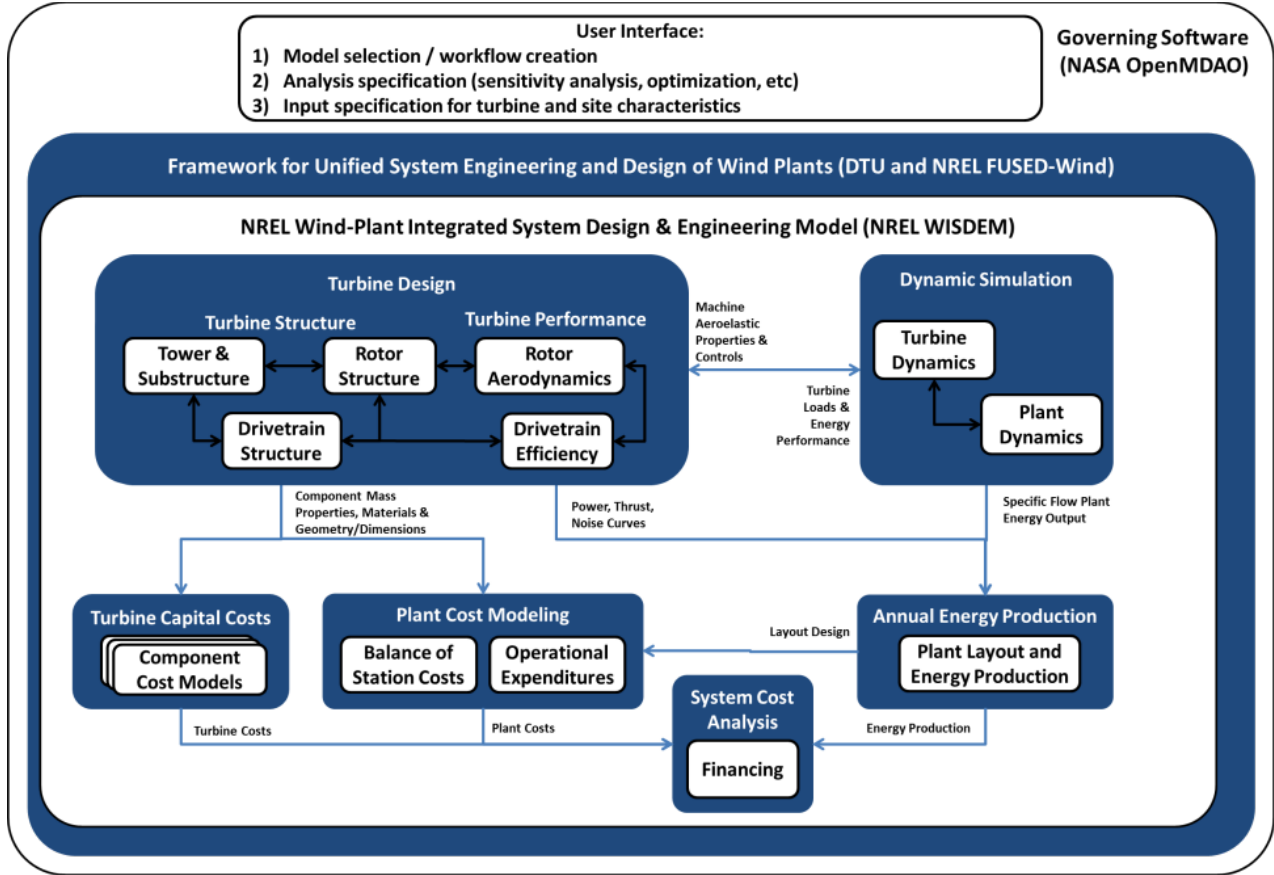
In this study, researchers applied WISDEM to a global sensitivity analysis to determine how key turbine configuration parameters affect overall system performance and cost and explore system-level relationships for different configurations of the system tool using different model combinations. In the past, global sensitivity studies have been applied to wind energy systems. For example, in a recent study by McKay et al. (2013), global sensitivity analysis was performed on a supervisory control and data acquisition (SCADA)-based, neural-network model of plant energy performance for an actual wind plant.<sup>2</sup> An earlier study used global sensitivity analysis methods in comparison with other approaches to assess the performance of a SCADA-based, neural-network model of wind turbine vibration.<sup>3</sup> Both cases emphasized how uncertainty in the inputs affected the output of a well-calibrated data-based model. Analysis of input-uncertainty impacts are a common use of sensitivity analysis methods. In this study, however, sensitivity analysis was used to explore the dependencies of a large complex-system model that were not known *a priori*. Although various previous studies have looked at multidisciplinary analysis and optimization of wind energy systems as catalogued by Dykes et al (2012), the use of integrated turbine and plant models is still an emerging area of research. Global sensitivity analysis was used here to assess the overall integrated model dependencies and interactions driven by changes in key turbine configuration parameters including rotor diameter, rated power, hub height, and maximum allowable tip speed. The analysis was performed with three separate system models ranging from low to moderate fidelity, and the results for each set are discussed with additional comparisons made across the three models. This leads to an understanding of the model dependencies and system interactions and how these will affect the integrity of more sophisticated analyses, including full system optimization studies. Finally, WISDEM's requirements in terms of additional development and potential application to future analyses are discussed.

## II. Approach

### A. Modeling with WISDEM

WISDEM couples engineering and cost analysis tools at all levels of the turbine—from individual components to the plant—to be able to perform analyses for system performance, cost, and external impacts such as is illustrated in Fig. 1. The overall tool involves the integration of wind turbine and plant models developed both internally and externally to NREL into the FUSED-Wind software framework to create the WISDEM system tool. In turn, the entire FUSED-Wind framework is to be built on the National Aeronautics and Space Administration's (NASA's) Open Multiple Disciplinary Analysis & Optimization (OpenMDAO) software.<sup>4</sup> Fig. 2 shows the overall tool with OpenMDAO as the central organizing software.

Models that represent different parts of the overall wind energy system (components, turbines, and plants) are linked together using the OpenMDAO software framework. These linked “assemblies” are then used to perform analyses that address questions concerning system behavior using various key indicators of performance and cost for a wind turbine and plant. These models reflect the important subsystems of a wind turbine itself, including the aerodynamic and structural models of a rotor, structural and power performance models of the drivetrain, and structural models of the tower and support structure (for either land-based or offshore wind plants). In addition, plant-level analysis was conducted with respect to overall energy production as well as costs for balance of station (BOS) and operational expenditures (OPEX), which include O&M costs. Models of different levels of fidelity from simple parametric to detailed physics-based models can be integrated together using the common structure provided by the software framework. These assemblies are then linked to “analysis drivers” such as (in this study) Sandia's open source Design Analysis Kit for Optimization and Terascale Applications (DAKOTA), which contains a large library of analysis algorithms for sensitivity analysis, optimization, uncertainty quantification, optimization under uncertainty, and more.<sup>5</sup>



**Figure 2. Structure of WISDEM model based on the FUSED-Wind framework to represent a full wind power plant.**

Analyses with broad scope can easily become intractable if not managed in a systematic way. For this analysis, researchers focused on estimating the overall levelized cost of energy (COE). The analysis of wind plant COE can be considered in many cases to be a global objective whereas other key system design criteria (such as plant noise) can be considered as system design constraints. In the simplest form, wind plant cost of energy can be computed by<sup>6</sup>:

$$COE = \frac{FR(TCC + BOS) + (1 - t)OPEX}{AEP_{net}} \quad (1)$$

Where  $COE$  is the levelized cost of energy for the wind plant,  $TCC$  is the turbine capital cost for the total number of turbines in the plant,  $BOS$  is the balance-of-station cost for all of the nonturbine capital costs associated with the design and development of a wind plant,  $FR$  is the financing rate associated with annualizing the capital costs for the plant,  $AEP_{net}$  is the estimated net annual energy production after all losses are accounted for,  $OPEX$  are the annual operational expenditures (including land-lease costs and O&M costs) for the plant typically based on an average annual value over its lifetime, and  $t$  is the tax rate that is used to adjust  $OPEX$ , which are tax deductible. To assess wind plant performance from a global COE perspective, each of the subcategories must be modeled. For this work, researchers used three model sets, each with a full system representation, to perform COE calculations. The details of each follow.

#### 1. NREL Cost and Scaling Model (NREL CSM)

The first model set uses the NREL CSM<sup>7</sup>, which is a simplified cost and scaling model developed in the last decade to assess the impacts of scaling relationships and input costs for labor and other factors on overall wind plant COE.<sup>8</sup> The model was originally developed as part of the Wind Partnerships for Advanced Component Technology (WindPACT<sup>9</sup>) and was derived via a series of curve fits based on detailed design studies conducted for a single land-based wind plant located in North Dakota and a variety of turbine sizes including 750 kW, 1.5 MW, 3 MW, and 5 MW. Relationships of key system design parameters (such as rotor diameter and hub height) to key system





from the underlying data set used by the NREL CSM. However, even a simple mass-based cost model for the components helps provide insight into how system design changes affect overall turbine costs because individual changes in all component designs are propagated to their costs. The TurbineSE and Turbine\_CostsSE models are briefly described.

### **Rotor Systems Engineering Model (RotorSE)**

The rotor systems engineering model represents the most involved effort in terms of the fidelity of the resulting analysis. Models for both the rotor aerodynamics, as well as its structure, have been developed. Details on the rotor modeling can be found in other publications.<sup>13,14</sup> The rotor model makes use of existing software tools, adds additional analysis capabilities and new software, and unifies these tools into a common framework. Aerodynamic analysis starts with blade-element momentum-based methods. This tool is extended to handle different control strategies (such as variable-speed and variable-pitch designs) as well as to evaluate additional metrics like annual energy production and noise. Additional modules have been developed to handle aerodynamic predictions of airfoil sections. A beam-element finite-element tool was developed to predict structural metrics such as natural frequencies, stress, and deflections. The resulting software allows for aerodynamic-only, structural-only, or joint aerodynamic and structural analysis of a wind turbine rotor (excluding the hub structure). The models combine information about external system conditions (environment and other subsystem loads) with information about an existing design (geometry, material properties, and configuration) to assess component performance in terms of overall mass, stress, and so on. RotorSE can then be used in an optimization setup to design a wind turbine rotor and blade structure.

### **Hub Systems Engineering (HubSE) and Nacelle Systems Engineering (NacelleSE) Models**

For the hub and drivetrain, with their many subcomponents and large number of potential configurations, researchers took a different approach for the initial phase of development. The hub and drivetrain models are based on the University of Sunderland Model<sup>15</sup> with some modifications influenced by the WindPACT efforts and the development of the NREL CSM. For the current models, all relationships for the main load-bearing components of the hub and nacelle subassemblies (including the hub, pitch system, low-speed shaft, main bearings, gearbox, high-speed shaft, braking system, generator, bedplate, and yaw system) were converted to a semi-empirical form based on the University of Sunderland model and calibrated to data based on current technology that underlie the current NREL CSM. Calculations of mass properties were added to the overall mass calculations.<sup>16</sup> Unlike the rotor model, the hub and nacelle component models resize themselves according to the loads from the rotor.

### **Tower Systems Engineering Model (TowerSE)**

The development of the integrated support structure model for a monopole tower on monopile foundation paralleled the development of the rotor. The same finite element code developed for the rotor structural analysis was adapted for use in the tower structural analysis. Researchers developed additional modules to characterize the environmental effects of wind loads, wave loads, and soil stiffness. An additional analysis on shell buckling, particular to tower analysis, was added using guidelines specified by the European Committee for Standardization as documented in Eurocode 3.<sup>17</sup> Inputs to the model include the materials and geometry (tower taper and wall thickness) of the overall structure. Outputs include calculation of the overall tower mass as well as performance under various rotor nacelle assemblies (RNA) and environmental loading scenarios. TowerSE can also be used in an optimization setup to design a wind turbine tower for land-based projects or an integrated tower/monopile for offshore projects.

### **Turbine Costs Systems Engineering (Turbine\_CostsSE) Model**

Data on turbine component costs is difficult to obtain because of the proprietary nature of the data. However, through various studies over the years, NREL has collected cost data on detailed system designs, such as those developed in WindPACT that can serve in the development of simple component mass-based cost models. As a result, mass-cost functional relationships were developed and a new turbine cost model was created. Researchers made a few additions to the models to account for the costs of assembly of the nacelle and hub subsystems as well as the general overhead costs and profit mark-ups imposed by the turbine supplier on the project developer. Researchers used general figures from production cost methods to translate the aggregate costs of the turbine components into an overall turbine cost. In particular, for this study, a markup of 30% was used to account for assembly costs related to the nacelle and hub as well as general overhead costs associated with wind turbine production.<sup>18</sup> An additional overall markup of 20% was then used to account for the difference in production cost to the supplier and the price as sold to the project developer.<sup>19</sup> From the turbine cost model, a turbine capital cost is calculated that can feed into an overall plant cost and financing model.



### 3. *Plant Models for Performance, Cost, and Financing*

#### **Plant Costs Systems Engineering (Plant\_CostsSE) Model**

Like the turbine subsystem models described above, the original NREL CSM for a wind plant model has been replaced by higher fidelity plant costs systems engineering (Plant\_CostsSE<sup>20</sup>) models. In collaboration with external partners, NREL has developed a new offshore balance-of-station cost model that more accurately reflects overall BOS costs for offshore wind projects and the relationships to input parameters, such as turbine subsystem weights and dimensions as well as plant characteristics of sea depth and distances to shore, that affect costs.<sup>21</sup> For operational expenditures, NREL has licensed the Energy research Centre of the Netherlands (ECN) Offshore O&M Model, which is undergoing adaptation for use in application to U.S. project OPEX estimates.<sup>22</sup> Each of these models provides significant capabilities for capturing important system interactions as well as representing costs that align with data from current projects. At the same time, however, there is still not a large amount of coupling between these empirical “top-down” plant-level models and the new bottom-up turbine systems engineering models. Some coupling is created between the turbine and plant models via the mass and critical dimensions of major components as well as individual component and overall turbine costs.

#### **Plant Annual Energy Production Systems Engineering (Plant\_EnergySE) Model**

In addition, there is coupling between the turbine and plant layout and energy production model. The plant energy-production systems engineering (Plant\_EnergySE<sup>23</sup>) model uses one of two models to estimate energy production. The first is a simple formulation where the power curve is convolved with the site wind speed resource Weibull distribution and multiplied by losses. This method is the same as the one used by NREL CSM. The second model uses AWS Truepower’s OpenWind wind plant design software, which uses information on the turbine including power and thrust curves, a GIS-based plant layout with layers for wind resource, topography, and so on, along with a simplified flow model to simulate energy production.<sup>24</sup> Multiple types of wake models can be used in conjunction with the flow model to understand how turbine-wake interactions affect energy production under different layout designs. For the purposes of the current project, only the energy production calculation features were used, though the model does provide BOS cost information as well.

#### **Plant Finance Systems Engineering (Plant\_FinanceSE) Model**

Currently, the plant finance systems engineering (Plant\_FinanceSE<sup>25</sup>) model offers the use of the simple NREL CSM cost of energy estimator based on Equation 1. The NREL CSM finance model was the only model used in this study because of its transparency and simplicity.

### 4. *Model Integration and WISDEM*

The overall WISDEM software is shown in Fig. 2. Here we will only briefly discuss the incorporation of the above model sets into the software. As mentioned earlier, for each of the different COE contributors (TCC, AEP, BOS, and OPEX), models of varying levels of fidelity can be used and capabilities of the NREL CSM can be combined with new WISDEM models. For this study, researchers used three different configurations of models, or model sets, in a comparative analysis. There are a large number of possible analysis configurations with just the two levels of fidelity. The three analysis model sets explore how increasing levels of fidelity in the employed models impact the results. In particular, moving from the highly abstract cost and scaling model to physics-based models for the turbine and more detailed cost and performance models for the plant is expected to preserve important interactions throughout the wind power plant system. These preservation would impact the sensitivity relationship of the system cost to the turbine configuration. The three model set-ups include 1) the use of the NREL CSM for the entire analysis, 2) replacement of the NREL CSM turbine models with TurbineSE and Turbine\_CostsSE and replacement of the NREL CSM plant cost models with Plant\_CostsSE models, and 3) additional replacement of the NREL CSM energy production model with Plant\_EnergySE using OpenWind.

The analysis begins with the simplest model set using NREL CSM and its built-in scaling relationships. Next, the TCC model is replaced by a set of models that include the new WISDEM TurbineSE models and associated Turbine\_CostSE model. Turbine design is fixed except for the scaling because of the sensitivity inputs. Structural performance of the turbine is evaluated using extreme wind load cases on the rotor and tower. In addition, the second model set configuration adds new Plant\_CostsSE models for plant BOS and OPEX. These are still empirical models but they are based on data for recent plants and involve a much larger set of input-output relationships than the NREL CSM plant cost models. Finally, the last analysis adds a plant layout and energy production model that allows for the investigation of turbine-wake interactions. The only model preserved in all three model sets is the NREL CSM finance model. Thus, the differences in the analysis results between the model sets are not affected by any financial factors and are only impacted by differences in the modeling of turbine and plant design and

performance. To allow for comparison across the model sets, the initial setup needs to be configured for the same wind project and the associated characteristics of the site, plant, and a reference turbine. This baseline for comparison was developed through the use of a reference project as discussed in the next section.

## B. Development of Offshore Reference Wind Plant

In order to perform sensitivity analysis for a full wind power plant system, a specification of the initial configuration for the project is needed. The WISDEM model sets include a relatively complete set of information about the wind plant, including detailed information about the wind turbine design and plant GIS information, which requires a wind resource grid at the turbine hub height. To avoid comparison against system performance and cost of actual wind plants, a hypothetical reference wind plant was created that incorporates the general features of a realistic wind power plant. For this study, the WISDEM model input set was calibrated for a hypothetical wind plant in the mid-Atlantic offshore region of the United States with a 5-MW International Electrotechnical Commission (IEC) Class IB turbine on a monopile foundation, as described in the following sections.

### 1. Reference Turbine Characteristics

The reference turbine used in this analysis is based on the NREL 5-MW offshore reference turbine (NREL 5 MW).<sup>26</sup> This turbine was initially created in 2006 to serve as a reference model that could be publically distributed, and since then it has been used in a variety of projects for comparing the performance of different wind turbine simulation models and assessing innovative technology concepts.<sup>27</sup> However, there are several limitations of the reference turbine model in terms of specifying a reference offshore wind plant representing today's technology. First, the original model sought to imitate the bulk properties of the few prototype turbines at the 5-MW scale at the time, but specifics about the commercial turbines were not available, and thus various aspects of the design, including the rotor, were based on other design studies such as the Dutch Offshore Wind Energy Converter project.<sup>28</sup> The turbine did not go through a rigorous design and optimization process and there are aspects of it that were considered to be overdesigned. In addition, the technology for very large (5 MW+) turbines has evolved since the model was created and, thus, the reference turbine is known to be out of date. However, the proper development of a reference turbine is a complex process beyond the scope of this work and the turbine used in this study is still very useful as a publically available and detailed description for a reference turbine. Table 1 provides turbine design parameters for NREL's 5-MW reference turbine.

**Table 1. Key Model Parameters for the NREL 5-MW Reference Turbine**

Turbine Design Parameters	Value
<b>Rotor Diameter</b>	126 m
<b>Rated Wind Speed</b>	12.1 m/s
<b>Cut-In/Cut-Out Wind Speeds</b>	3 m/s; 25 m/s
<b>Maximum Allowable Tip Speed</b>	80 m/s
<b>Hub Height</b>	90 m
<b>Tower Length/Monopile Length</b>	60 m; 30 m
<b>Tower Top/Base Diameters</b>	3.87 m; 6.0 m
<b>Drivetrain Configuration</b>	three-stage geared with induction generator
<b>Rated Power</b>	5 MW
<b>Gearbox Ratio</b>	97:1
<b>Drivetrain Efficiency at Rated Power</b>	94.4%

The NREL 5-MW reference turbine still needs some adaptation for use in a full system model. The properties of the turbine necessary to simulate its behavior with various aero-elastic codes are insufficient to build out a full cost model. For cost modeling, structural and material design information about different components of the turbine are needed. For instance, if the rotor diameter of the blade changes, keeping all other design parameters the same and scaling the rotor properties uniformly with the diameter will increase the mass of the blade. As a result, this change in mass will be reflected in the cost of the blade output by the turbine cost model. The level of detail required for each component's design depends on the level of the fidelity of the individual component models. The structural models for the rotor blades and tower require information about the materials and dimensions of the structures at a series of points. Sufficient information about the tower and monopile, which are relatively simple structures, can be found in the NREL 5-MW turbine description. However, a cost model for the rotor blades requires additional information, and detailed structural layout data for the rotor blade cross-sections are not provided in the NREL 5-

MW reference turbine report. Thus, detailed structural and material information on the reference turbine blades are based on reverse engineering of the blade properties by Resor at Sandia National Laboratories.<sup>29</sup>

The hub and drivetrain models were scaled directly from the rotor loads so that no further design information was necessary beyond the bulk parameters provided in Table 1 and the input loads from the rotor. The reference model outputs were compared to data on component sizes in the NREL CSM, data from WindPACT, and a limited set of information on commercial turbine designs.

## 2. General Site and Plant Characteristics

Unlike the NREL 5-MW reference turbine, no public description of a hypothetical offshore reference wind plant was available for this study. The use of a specific site was avoided to the extent possible and any remaining site-specific data are masked. Any comparison to an actual project would be spurious as the information used in the model specification represents composite statistics on proposed United States offshore wind plant projects. The site characteristics below depict a hypothetical reference wind plant in the mid-Atlantic region of the United States in federal waters (beyond 3 nm from shorelines for most states). Over 10 years of hind cast, wind/wave data were used to develop statistics for wind speed, wave height, and wave period distributions and joint distributions. Representative key statistics from the data analysis were used in the analysis of the turbine and plant models as described in Table 2.<sup>vii</sup>

**Table 2. Key Reference Site Characteristics**

Key Site Parameters	Value	Comments
Distance to Shore	30 km	Distance to site from the staging port can vary substantially depending on the project – 30 km is a reasonable estimate
Sea Depths	20 m	NREL 5-MW reference turbine assumes a 20-m depth – data from OpenWind site vary from 10 to 30 m with a concentration in the 20- to 25-m depth region
Wind Speed at 90 m	Mean = 8.65 m/s Weibull shape factor = 2.1	Hub height mean annual wind speed indicates borderline class I wind site such that there is an extreme 50-year wind speed gust of 70 m/s
Design Wave Height	10-year extreme = 6.0 m 50-year extreme = 8.0 m	50-year extreme significant wave height similar to extrapolation of hind cast data tail distribution for mid-Atlantic sites; no extreme individual wave information was available
Design Wave Period	10-year extreme = 20 s	Maximum value similar to mid-Atlantic hind cast data sets

An OpenWind model was developed using data from a particular site for a wind resource grid and bathymetry. The site was selected because of its location in relatively shallow water (as shown in Fig. 4) and its agreement with the use of the NREL 5-MW reference turbine in 20 m of water depth on a monopile foundation.



**Figure 4. Bathymetry image of the reference site.** The light gray color indicates depth < 15 m, the darker gray color indicates depths between 15 and 25 m, and the black color indicates depths > 30 m (modeled in OpenWind). A majority of the site is located in water depths of ~20 m with the plant perimeter roughly indicated by red outline.

<sup>vii</sup> The hindcast data comes from the Army Corps of Engineers Wave Information Studies project <http://wis.usace.army.mil/wis.shtml>. Data are provided in 3-hour increments and analyzed to produce the site statistics. Documentation on the project can be found at [http://wis.usace.army.mil/WIS\\_Documentation.shtml](http://wis.usace.army.mil/WIS_Documentation.shtml).

The wind characteristics of the site were compared to the parameters used for the NREL 2011 *Cost of Wind Energy Review*, which based its analysis on a wind plant with an average annual wind speed of 8.4 m/s at 50 m, and a Weibull shape factor of 2.1.<sup>30</sup> The assumed wind shear was 0.1 leading to a 90-m average annual wind speed of roughly 8.9 m/s. Although the NREL review estimated a higher annual average wind speed, several sites that are likely to be developed in the near term—those closer to shore—have lower estimated average annual wind speeds. The specific reference site is characteristic of these lower wind speed sites located closer to shore. The wind resource grid used in the OpenWind model includes point values whose mean 90-m wind speed distributions vary with mean annual wind speed averages falling entirely between 8.6–8.8 m/s.

### C. Global Sensitivity Analysis of System Cost and Performance to Key Turbine Configuration Parameters

In this work, researchers evaluated the global sensitivity of overall system COE and performance measures to changes in the key turbine configuration parameters of rotor diameter, hub height, and rated power. Simplified models of wind energy systems often characterize the turbine in terms of these configuration parameters and their selection has a significant impact on overall turbine design. In addition, the researchers assessed sensitivity to another design parameter of importance: maximum allowable tip speed. The maximum allowable tip speed affects overall turbine design and system cost, but it also has important implications for the aero-acoustic noise produced by the turbine, that in turn can impact communities located near a wind plant.<sup>31</sup> The four turbine configuration parameters will be assessed in a collected global sensitivity analysis.

Sensitivity analysis can be categorized as local, focusing on small perturbations in input parameters, such as those associated with unit changes in constraint variables used in an optimization, or they can be categorized as global, looking at how variations in parameters over their entire ranges affect system output. This study is focused on the latter. In particular, Monte Carlo sampling methods built into DAKOTA were used to perform global sensitivity analysis over a multidimensional input space to generate 1) scatter plots and associated curve fits, 2) correlation matrices<sup>viii</sup>, and 3) Sobol indices via variance-based decomposition.<sup>32</sup> Scatter plots, curve fits, and correlation matrices were particularly useful for comparing the relative influence of input parameters on overall model outputs whereas Sobol indices were useful in understanding transfer of variance from input to output parameters as well as system interactions. The two Sobol indices characterized the variance of the outputs in terms of an input. The Sobol index “main effect”,  $S_X$ , is the variance in the output variable Y caused by the variance in input variable X:

$$S_X = \frac{V(E(Y|X))}{V(Y)} \quad (2)$$

Thus, the Sobol index main effect gives an indication of how strong the direct influence of X is on Y without any interactions with other variables. The “total effect”,  $T_X$ , then, is the main effect of the variance in variable X on the output variance of Y plus the effects from variance of the interaction of variable X with all the other variables ( $\sim X$ ) in the system. Mathematically it can be shown that this is equivalent to subtracting from one the variance in the output due to  $\sim X$  normalized by the overall variance of the output:

$$T_X = 1 - \frac{V(E(Y|\sim X))}{V(Y)} \quad (3)$$

In other words, the Sobol index total effect gives an indication of the total influence of X on Y from its own direct effects along with its interaction with other variables. The differences between the main effect and the total effect then give an indication of how important the interactions of X are with other variables in influencing Y. If the main effect is small, whereas the total effect is large, then X does influence Y but only through interactive effects with other system inputs. For this study, the use of Sobol indices will help us assess the importance of system interactions in each analysis and compare the changes in interactive effects between the three different analysis configurations. For detailed discussion on Sobol indices and more general discussion on global sensitivity analysis, see Satelli et al. (2008) and related publications.

McKay et al. (2013) and Kusiak et al. (2010) used a computationally efficient method to calculate the Sobol indices based on the Fourier Amplitude Sensitivity Test (FAST) method. However, the complexity of the models

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<sup>viii</sup> Correlation matrices provide standard (Pearson) correlation coefficients between variables calculated as the covariance between two variables divided by the standard deviation of the variables multiplied together.

used in this study did not necessitate the use of the method and DAKOTA's straightforward Monte Carlo-based approach was suitable for the three analyses. As complexity of the models increases, it would become necessary to use FAST or derivative methods.

Researchers performed the analysis for global sensitivity using the aforementioned input parameters of rotor diameter, hub height, power rating, and maximum tip speed. System outputs included COE and the contributing factors of TCC, AEP, BOS, and OPEX. In addition, for the higher fidelity models, analysis included several turbine performance variables relating to design margins on the rotor and tower in particular. The global sensitivity analysis was performed using the three different model sets to explore how increasing levels of fidelity in the subject models would impact the results. Specifically, moving from the highly abstract cost and scaling model to physics-based models for the turbine and more detailed cost and performance models for the plant was expected to preserve important interactions through the system, which would impact the sensitivity relationship of system cost to the turbine configuration.

### III. Results

#### A. Comparison of Reference COE across Model Sets

As mentioned previously, the input characteristics for the turbine and plant in the analysis were based on the NREL 5-MW reference turbine and a hypothetical offshore reference project in the mid-Atlantic region of the United States. The selection of the site and corresponding data were further informed by the NREL *2011 Cost of Energy Review*,<sup>ix</sup> which reported overall COE trends for offshore projects in Europe along with projections for a United States reference project cost. The reported estimate for plant COE for a U.S.-based project was \$0.225/kWh, with total installed capital costs including financing of \$5600/kW. This calculation was in general agreement with the model results for the newer models sets shown in Table 3.<sup>x</sup>

**Table 3. Comparison of Cost Model Results for Baseline 5-MW Turbine Design in a 100 Turbine Project**

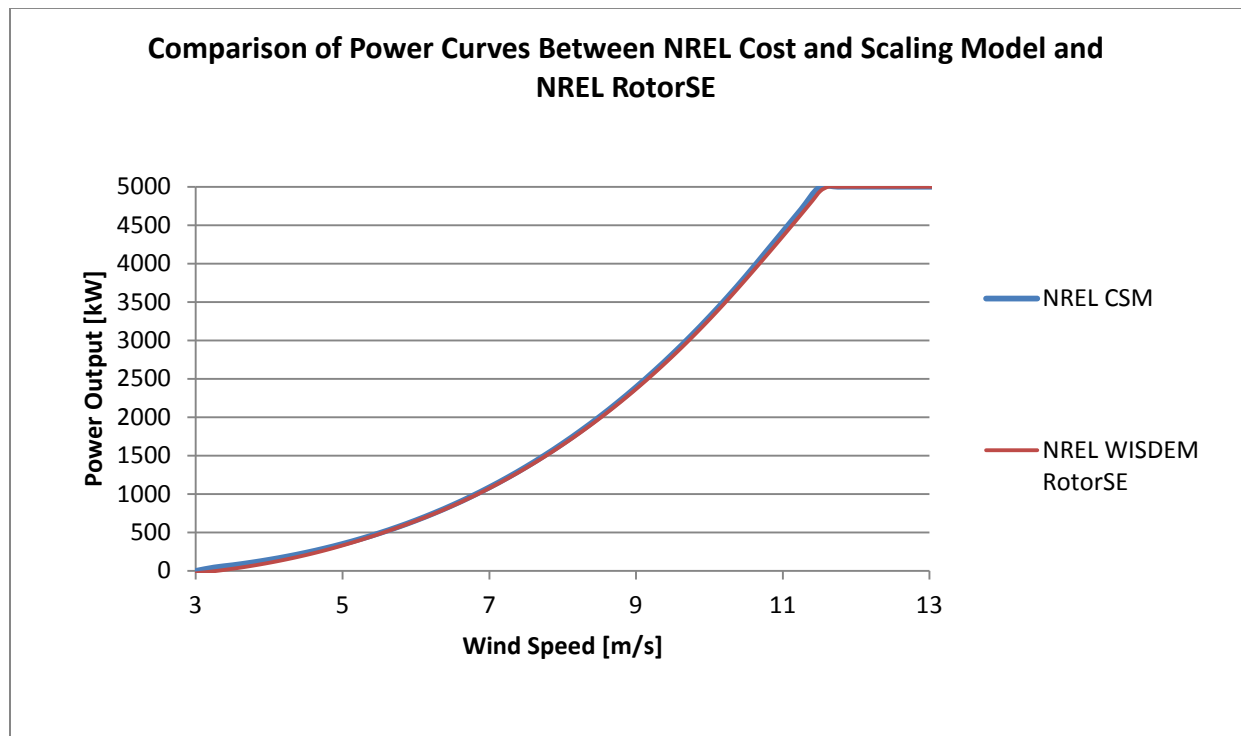
	NREL CSM	NREL w/ TurbineSE & Plant_CostsSE Models	NREL w/ TurbineSE, Plant_CostsSE Models & OpenWind
<b>LCOE (\$/kWh)</b>	\$0.11	\$0.20	\$0.20
<b>AEP (kWh/turbine/year)</b>	18,113,563	18,079,737	18,667,378
<b>Turbine Cost (\$/kW)</b>	\$1,190	\$1,848	\$1,848
<b>BOS Costs (\$/kW)</b>	\$1,533	\$3,505	\$3,505
<b>OPEX (\$/kW/year)</b>	\$100	\$121	\$121

Note: COE calculated using standard NREL analysis methods including a project lifetime of 20 years, a fixed charge rate of 12%, and an operational expenditure tax deductible rate of 40%.

<sup>ix</sup> Certain aspects of the models were calibrated to bring the initial model results for BOS costs into agreement with the review results. These calibrations included multipliers of 1.5 and 1.3 for the electrical and vessel costs, respectively, as well as the addition of costs for project management at \$56 USD/kW and a construction financing multiplier of 1.03 on the total installed capital costs. Financing assumptions were based on the NREL *2011 Cost of Energy Review* and included a fixed charge rate of 0.12 and a tax deduction rate of 0.4 on OPEX. In addition, an offshore warranty premium was used in the finance model that placed a 15% multiplier on the turbine cost and a subsequent turbine marinization cost of 10%. Both of these multipliers are used by the NREL CSM. The turbine cost reported below included the marinization cost and the warranty premium was applied in the cost of energy calculation itself (to the turbine cost prior to application of the multiplier for turbine marinization).

<sup>x</sup> The COE for the latter two cases using the new WISDEM models differs slightly from the NREL *2011 Cost of Energy Review* due in particular to slightly lower BOS costs than those from the \$3811/kW reported in the review. In addition, the energy production capacity factor for the reference site at ~0.43 is higher than that of the review value of 0.39, which brings down its cost of energy to \$0.20/kWh compared to the \$0.225/kWh value reported in the review. Overall, the results for the WISDEM models were in the range of reported costs for actual wind plants, which served as the basis for the review analysis.

Between the three analyses, however, there were some notable differences. These differences have to do primarily with the increased fidelity of the newer models for different aspects of the wind plant. First, AEP between the three models differs by a small amount (maximum of 3%). The power curve created by the WISDEM RotorSE tool using an aerodynamic model produced slightly less power at the transition to region 3 leading to slightly less overall energy calculated from convolution with the site Weibull wind speed distribution. The power curves generated from each analysis are shown below. The array losses for the two prior analyses were calibrated to the OpenWind array losses of 5.9% so that the key difference from the first two analyses to the use of OpenWind was that the wind resource varied with location. Thus, the average statistics used in the two prior cases resulted in lower AEP estimates. Nonlinearities in the system mean that using average statistics is flawed, exemplified by the use of spatially-averaged wind resource statistics for energy production calculations in the first two analyses. However, even OpenWind is limited by the use of time-averaged wind resource statistics for energy production calculations and higher fidelity is still possible.



**Figure 5. Power curve for different model approaches.**

The turbine capital costs are significantly higher for the new WISDEM Turbine\_CostsSE model versus the NREL CSM. This is primarily due to the fact that the new cost model incorporates additional costs for the assembly of nacelle and hub systems and overhead, resulting in a 30% cost addition to the turbine and a markup of 20% from the turbine supplier to the project developer. Such costs were not included in the NREL CSM, which created a turbine cost solely based on the sum of the individual component costs. However, the data for component cost estimation are the same between the two models, and the individual turbine and costs between the two models were in good agreement. The mass and cost comparison is shown in Table 4. The hub system model based on the University of Sunderland model predicted much higher mass values, but the differences were canceled out in calculation of overall turbine mass because of lower predicted gearbox and nacelle component masses. The non-load-bearing components in the new Turbine\_CostsSE model still rely on the mass calculations of the older NREL CSM such that their masses and costs do not change between the two models.

The new NREL offshore BOS model provided costs that were more than double the costs provided by the original NREL CSM. The limitations of the NREL CSM for offshore BOS modeling were known and the new model was more representative of the actual expected costs in this area. Finally, the ECN Offshore O&M model projected slightly higher costs than the NREL CSM. The NREL CSM for offshore O&M was highly simplified (a multiplier of AEP) and the new model, calibrated to field data for European projects, was expected to be a more



accurate assessment of O&M costs. In fact, the NREL *2011 Cost of Energy Review* estimated reference project costs to be even higher than the predicted costs from the ECN Offshore O&M model.

**Table 4. Turbine Component Masses and Costs from the NREL CSM and Turbine\_CostsSE Models**

	NREL CSM Component Masses	NREL Turbine_CostsSE Component Masses	NREL CSM Component Costs	NREL Turbine_CostsSE Component Costs
<b>Rotor</b>	<b>87,596</b>	<b>106,800</b>	<b>\$1,133,729</b>	<b>\$1,285,166</b>
Blade	52,952	53,118	\$754,578	\$759,631
Hub	22,519	34,405	\$124,902	\$190,827
Pitch System	10,314	17,466	\$243,740	\$324,199
Spinner/Nose Cone	1811	1811	\$10,509	\$10,509
<b>Nacelle</b>	<b>215,112</b>	<b>214,389</b>	<b>\$3,266,052</b>	<b>\$3,110,140</b>
Low-Speed Shaft	33,121	32,319	\$178,934	\$188,878
Main Bearings	5401	10,182	\$125,778	\$237,126
Gearbox	37,991	31,905	\$915,280	\$673,965
Mechanical Brakes	995	1575	\$10,143	\$16,057
Generator	16,700	16,700	\$418,156	\$435,158
Variable-Speed Electronics	0	0	\$507,185	\$507,185
Electrical Connections	0	0	\$338,197	\$338,197
Hydraulics and Cooling	400	400	\$80,833	\$80,833
Controls	0	0	\$68,852	\$68,852
Yaw System	13,152	12,188	\$154,277	\$141,191
Mainframe	100,517	100,024	\$404,291	\$358,574
Nacelle Cover	6837	9097	\$64,125	\$64,125
<b>Tower</b>	<b>444,384</b>	<b>434,559</b>	<b>\$1,009,500</b>	<b>\$988,020</b>
<b>Turbine</b>	<b>747,092</b>	<b>755,748</b>	<b>\$5,950,209</b>	<b>\$9,237,788</b>
* Includes assembly, overhead, and turbine supplier mark-up				

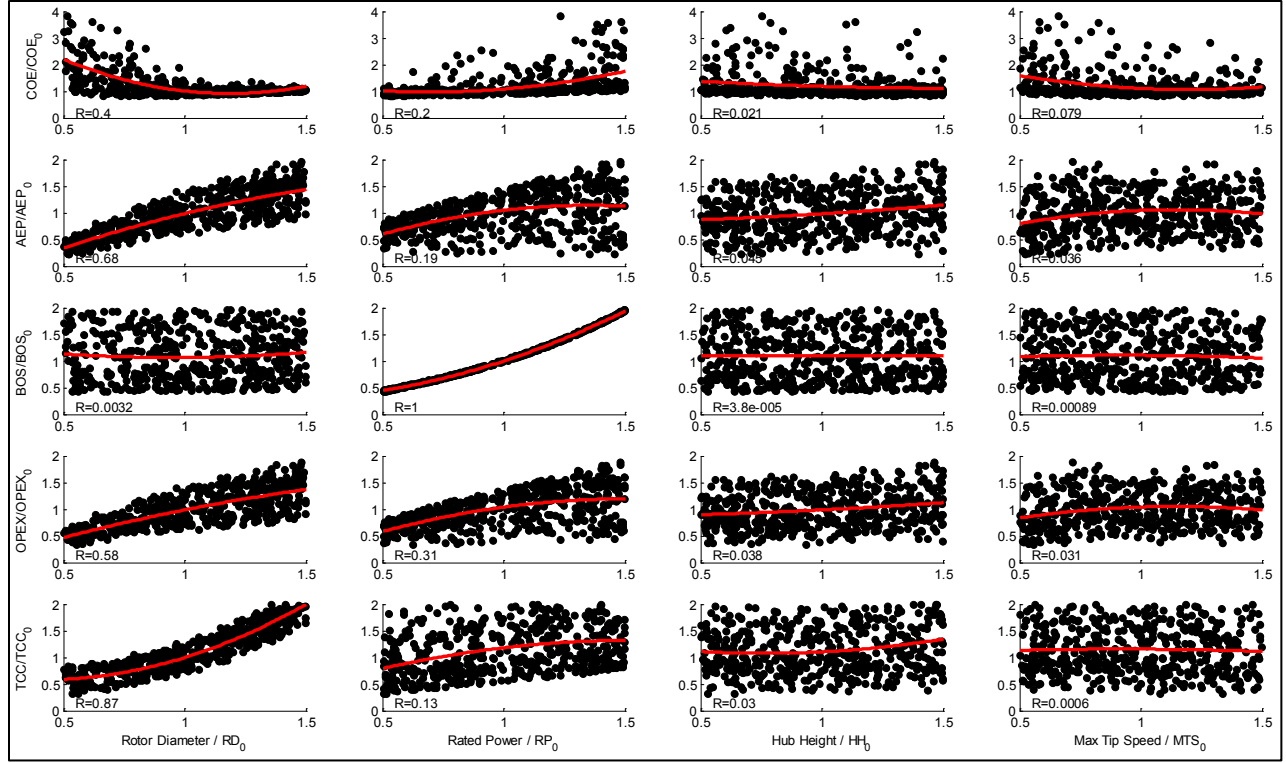
## B. Global Sensitivity of Cost to Key Turbine Design Parameters

The results of each individual sensitivity study are presented below. The discussion begins with the simplest model—the NREL Cost and Scaling Model—followed by the higher fidelity model sets. In each case, uniform distributions of 0.5 to 1.5 times the reference values for the key turbine configuration parameters of rotor diameter, rated power, hub height, and maximum allowable tip speed were sampled via a Monte Carlo process with a sample size of 500.

### 1. NREL Cost and Scaling Model

The first results presented are from a sensitivity study on the NREL CSM. The output variables of interest for this model set included COE and its constituent components of TCC, AEP, BOS, and OPEX. Turbine component masses and overall turbine mass are other important sets of model outputs, and the turbine mass was included as one of the analysis response functions. The resulting scatter plots are provided in Fig. 6 as well as polynomial quadratic curve fits and the associated coefficient of determination,  $R^2$ , for each curve fit.<sup>xi</sup>

<sup>xi</sup> The standard definition of  $R^2$  is used here, which is the sum of squares of the residuals over the sum of squares of the total, all subtracted from one.



**Figure 6. Scatter plots and curve fits for the NREL CSM global sensitivity analysis.** *Input and output variables have been normalized against reference values as described in Section III.B. The curve fit  $R^2$  values are provided above (denoted as  $R$ ).*

A global sensitivity analysis of the NREL CSM was not expected to yield surprising results. The model is a highly abstracted set of parametric relationships designed to map changes in key design parameters, like the ones selected for this study, in relation to changes in system cost. The limitations of the model in terms of representing outdated technology and cost data have already been mentioned. However, the sensitivity study here further exposes limitations of the model built into its design. In particular, the model is revealed to be sensitive primarily to two input variables while the remaining two have less influence than would be expected. These four variables are the most influential turbine parameters in the model (as illustrated in Fig. 3), which means that the model is significantly determined by the selection of just two variables: rotor diameter and rated power. Rotor diameter has a visible direct impact on all COE constituent variables with the exception of BOS, which is dependent entirely on rated power. Hub height, surprisingly, has little to no influence on plant energy production (in which the output is impacted jointly by the site wind shear and the hub height of the turbine), nor on turbine capital costs (where hub height should affect tower size and cost and the loads and design of the rotor and nacelle), nor on BOS costs (in terms of transport for the tower and overall installation costs). A similar argument can be made for the allowable tip speed that should (in extreme cases) affect energy production and turbine loads, sizing, and costs. This is further illustrated via the correlation coefficients from the study.

**Table 5. Correlation Coefficients across Inputs and Outputs for the NREL CSM Sensitivity Analysis**

	rotor diameter	rated power	hub height	maximum tip speed	COE	AEP	BOS	OPEX	TCC	turbine mass
COE	-0.50	0.42	-0.14	-0.24	1.00					
AEP	0.82	0.41	0.21	0.15	-0.49	1.00				
BOS	0.02	0.99	0.00	-0.02	0.43	0.40	1.00			
OPEX	0.76	0.54	0.19	0.14	-0.38	0.99	0.53	1.00		
TCC	0.91	0.35	0.15	-0.01	-0.27	0.89	0.35	0.88	1.00	
turbine mass	0.90	0.12	0.34	-0.08	-0.37	0.82	0.12	0.78	0.95	1.00

Correlation coefficients between the rotor diameter, rated power, and the various outputs are relatively strong with the exception of rotor diameter on BOS (which is entirely dependent on rated power) and rated power on turbine mass, as it only affects the generator mass with the mass of other electrical components neglected in the model. The dependency of OPEX on the intermediate variable AEP is also illustrated with the correlation coefficient of 0.99. Hub height has only limited influence on turbine mass and cost where it directly impacts tower mass and cost; maximum allowable tip speed has no appreciable effect on the model though there is a small positive correlation between it and AEP. Note, however, that the wind shear coefficient for the site is fixed at a relatively low value of 0.10 for this particular offshore reference site. For other sites and land-based sites in particular, it would have an even higher effect. As the wind shear exponent increases, so does the correlation between hub height and energy production, which is expected. This, in turn, increases the magnitude of the correlation between hub height and COE (doubling the wind shear to 0.20 results in a change in the correlation coefficient from -0.09 to -0.21). The site characteristics are not part of this turbine-focused study, but it is important to remember that they play an important role in the determination of overall plant cost and performance and that they can interact significantly with the turbine design parameters and change the sensitivities.

Regarding the direction of the relationships, rotor diameter, hub height, and maximum tip speed all have negative correlations with overall COE. However, of the three variables, the only really strong relationship both in terms of the correlation coefficient and the visible dependency in the scatter plot is between rotor diameter and COE. As the rotor diameter is reduced, the AEP is reduced, as are OPEX (which depends entirely on AEP) and TCC. These effects somewhat cancel each other out. However, BOS is unaffected (because it depends on rated power alone) and thus the overall COE starts to grow quickly as the rotor diameter continues to decrease. Similarly, for increases in rotor diameter, AEP, OPEX, and TCC increase, whereas BOS is unaffected (again)—such that overall COE tends to decrease. Rated power, on the other hand, has a less substantial overall impact on COE because it includes an impact on BOS. There is a slight positive correlation between rated power and COE (also noticeable in the scatter plot) because increasing rated power will increase AEP, OPEX, TCC, *and* BOS.

The rank correlation coefficients<sup>xii</sup> show the same trends among the variables as discussed above and provide further evidence of the strong dependency of the outputs on rotor diameter and rated power, and little to no relationship to hub height and maximum allowable tip speed. The NREL CSM, as one of the only publically available system cost models for wind energy, has been used in many turbine design studies to provide an overall system objective of cost minimization, but the model is really only sensitive to two high-level design parameters, which makes it spurious for such use. The fact that BOS and OPEX are wholly determined by rated power and AEP, respectively, is illustrative of the simple nature of the model. Furthermore, the model captures only limited effects of interactions between variables and primarily, again, those interactions between rated power and rotor diameter. The Sobol indices for the model show strong main and total effects for both rotor diameter and rated power with negligible influence from hub height and some minor interaction effects of maximum allowable tip speed with the other variables.

**Table 6. Sobol Indices for Inputs on COE Response of the NREL CSM**

	<b>Main Effect</b>	<b>Total Effect</b>
<b>Rotor Diameter</b>	<b>0.30</b>	<b>0.55</b>
<b>Rated Power</b>	<b>0.24</b>	<b>0.36</b>
<b>Hub Height</b>	0.02	0.05
<b>Maximum Tip Speed</b>	0.12	<b>0.22</b>

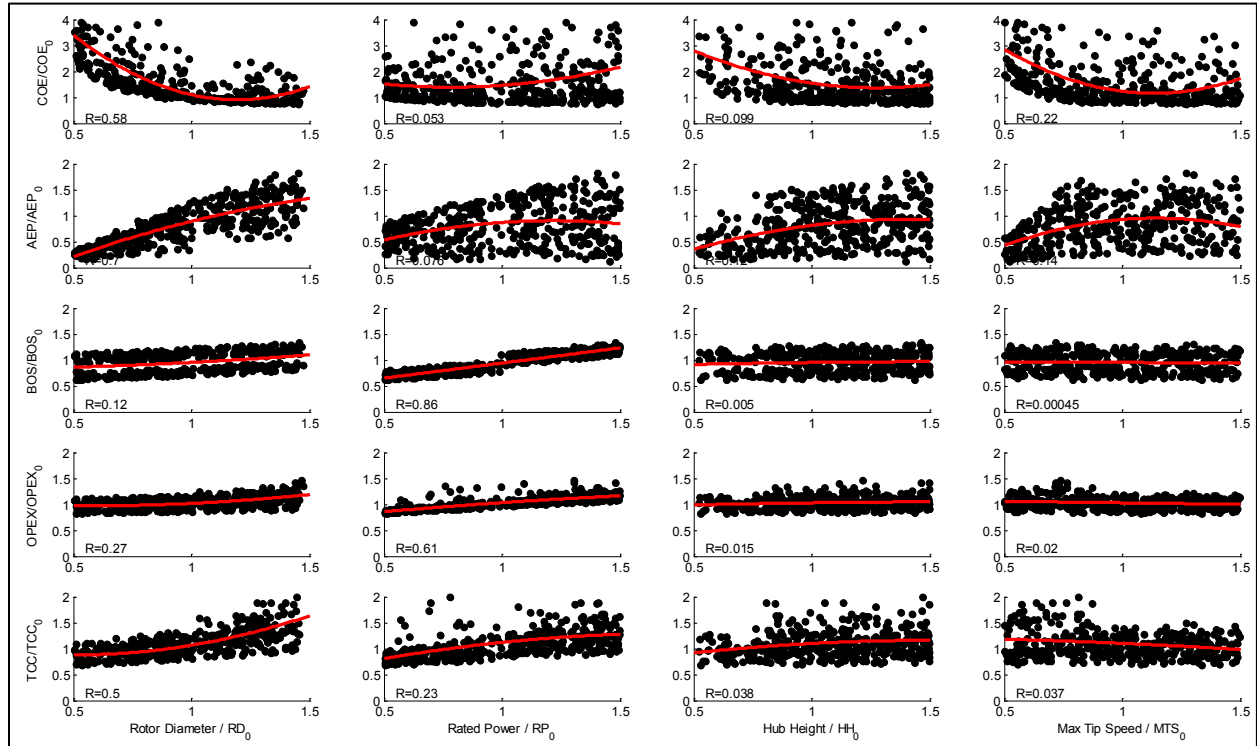
Although the NREL CSM is useful for some limited scaling applications, the oversensitivity of the model to two parameters and the lack of representation of important system interactions render it inadequate for understanding how most system design changes will affect overall performance and cost. More fidelity in all parts of the model is needed to capture the important interactions characteristic of real wind energy plants.

<sup>xii</sup> Rank correlation coefficients are defined as the Pearson correlation coefficients between ranked variables where input vectors X and Y are ordered and their ranks are used as inputs to the correlation coefficient calculation. This provides a measure of the tendency of variables X and Y to move in the same direction. This is often used as an alternative measure of correlation where dependencies are non-linear or where there may be outliers in the data.

## 2. WISDEM

The same overall software tool was modified to include an assembled model set in OpenMDAO where the NREL CSM turbine scaling model was replaced by fully physics-based models for the support structure and rotor blades and semi-empirical sizing models for the hub and drivetrain. The NREL CSM cost models for the turbine, BOS, and OPEX were all replaced with models of slightly higher fidelity, models that depend on multiple turbine parameters and are updated for current turbine technologies. A global sensitivity analysis was performed using the same setup as before with additional output parameters on the turbine performance, in particular for stress and design margins along the blades and tower. This was done because the new physics-based models for the rotor and tower have a number of design parameters that are independent of rotor diameter and hub height, respectively. For the blades, the rotor diameter is scaled, so is the blade length, but everything else remains the same except for a proportional scaling of position with the new blade length. This scaling includes key blade design parameters, such as distributions for chord, twist, airfoil selection, spar cap thickness, and so on. Not adjusting these parameters as rotor diameter changes results in unrealistic designs for extreme rotor diameter values. For instance, as the rotor diameter increases, keeping the chord and twist profile the same will result in an unrealistically low solidity and mass for the blades for that diameter. The same could be said for the airfoil profiles and the structural makeup of the blade. In an extensive analysis, the aero-structural design of the blade could be optimized by varying a large number of parameters and considering a large number of constraints.

In this study, we are leaving optimization out, and thus we only capture the sensitivity of the turbine design to rotor diameter, keeping everything else the same. Instead, we look at the structural performance of the rotor as an indication of the validity of the sensitivity results as the rotor diameter changes. The maximum compressive stress and associated design margins along the blades at their maximum airfoil thickness points under extreme loads comprise one set of variables that indicates how the turbine should be modified as the rotor diameter and other variables change. Similarly, as the hub height increases, one would expect to have to redesign the tower thickness and diameter along its length. Instead, this study keeps these parameters the same and tower design margins under extreme loads provide an indication of design validity. A thorough sensitivity analysis would allow for reoptimization of the full turbine. Such a study could have hundreds to thousands of design variables and constraints. In this study, we are doing a first pass to look at the integrated system model sensitivities without redesigning the turbine or plant. Fig. 7 shows the scatter plot results from a global sensitivity on WISDEM.



**Figure 7. Scatter plots and curve fits for the WISDEM global sensitivity analysis.** *Input and output variables have been normalized against the reference values described in Section III.B. The curve fit  $R^2$  values are provided above (denoted as  $R$ ).*

At first glance, there is a noticeable reduction in scatter in the plots for many of the relationships and there are noticeable trends between most of the turbine configuration variables and the aggregate cost and performance variables. The changes in the  $R^2$  values for the hub height and maximum tip speed relationships generally increase, which supports the idea that there are both more dependencies and system interactions included in the updated model set. However, the new model set also introduces a few shortcomings of its own. In addition to the lack of suboptimization of the rotor and tower, there are some idiosyncrasies to the new plant cost models. The most noticeable is in the new OPEX model that uses the ECN Offshore O&M analysis model. In the NREL CSM, plant OPEX figures were tied entirely to AEP as a proxy for the loads-induced O&M costs on the turbines. Rotor diameter and rated power, which had a strong influence on AEP, also heavily influenced OPEX. In this new model, OPEX is relatively insensitive to all four turbine parameters and varies over a small range. At present, the only significant inputs to the ECN Offshore O&M analysis model are overall turbine cost. The turbine and plant component failure rates are built into the model and are based on empirical data from projects in Europe. There is no bottom-up model of turbine and plant component failures that would update these parameters as the turbine design changes. Thus, changes in OPEX are tied to changes in TCC only. The result is that there is a slight increase in OPEX caused by rotor diameter and rated power, but not as much as would be expected from varying those parameters over such an extreme range. Similarly, the BOS model still shows an overall strong dependency on rated power, though the  $R^2$  and correlation coefficients are now less than one, as seen in Table 7.

**Table 7. Correlation Coefficients across Inputs and Outputs for the Sensitivity Using New WISDEM models.**

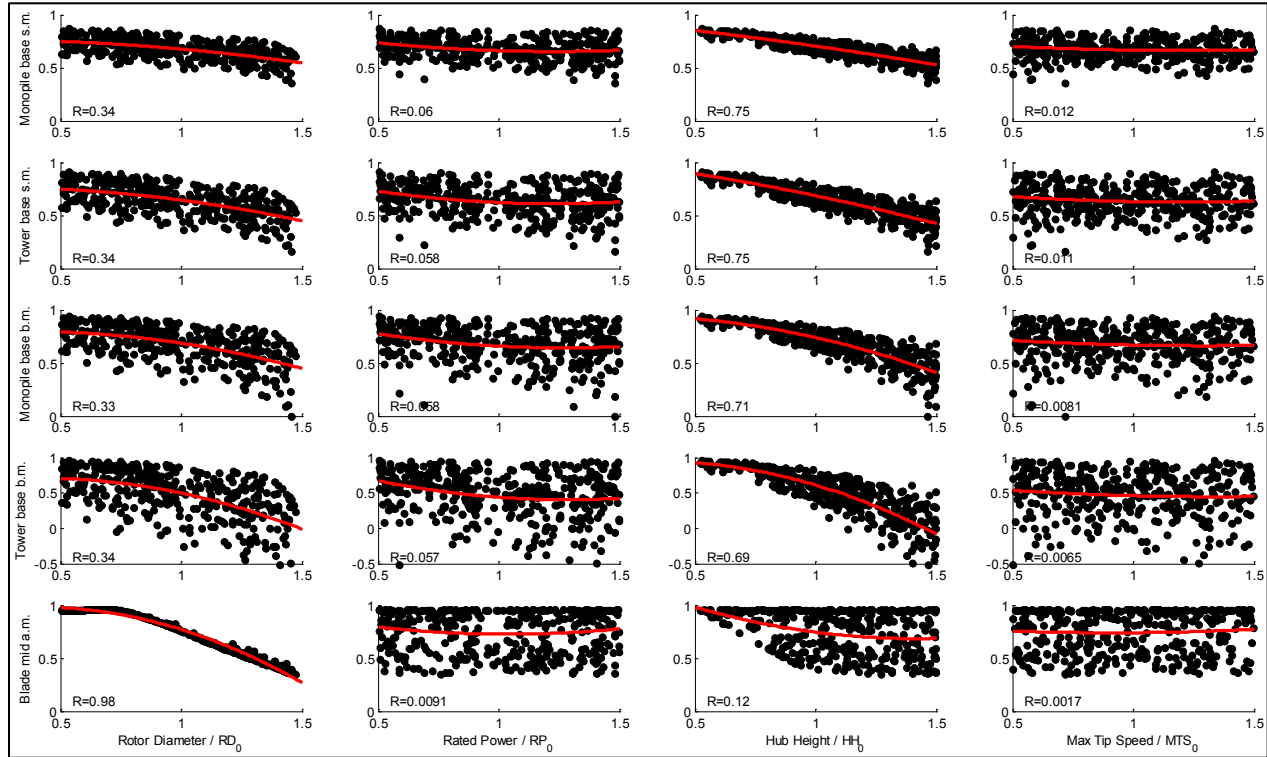
	rotor diameter	rated power	hub height	maximum tip speed	COE	AEP	BOS	OPEX	TCC	turbine mass
COE	-0.66	0.20	-0.27	-0.35	1.00					
AEP	0.83	0.24	0.33	0.29	-0.76	1.00				
BOS	0.35	0.93	0.07	-0.02	-0.04	0.49	1.00			
OPEX	0.49	0.78	0.12	-0.14	-0.13	0.55	0.89	1.00		
TCC	0.68	0.47	0.19	-0.19	-0.31	0.62	0.67	0.92	1.00	
turbine mass	0.77	0.25	0.21	-0.19	-0.42	0.65	0.49	0.80	0.97	1.00

The correlation between rated power and BOS dropped from 1.0 down to 0.93, but is still very strong. The strong correlation is principally because the model costs are driven primarily by project size (total rated power = turbine rated power \* number of turbines). In this study, the project characteristics (number of turbines) were fixed so that the overall project size was greatly affected by the large range of rated power that was sampled, as a result, the overall BOS costs fluctuated strongly with rated power. In real projects, the number of turbines and rated power would typically be joint design inputs with an overall target size in megawatts for the plant. The overall correlation between rated power and COE is positive, due in part to the strong relationship between rated power and BOS. However, inspection of the scatter plot for this relationship shows that this relationship is weak with a very low  $R^2$  value. Rated power has a positive relationship with AEP, BOS, OPEX, and TCC such that the overall effect on COE is minimal.

Rotor diameter, on the other hand, still has a strong impact on all output variables and the strongest correlation to COE (in a negative direction). Rotor diameter still has a positive relationship to turbine mass and TCC. However, in this case, the relationship is driven not just by a scaling relationship but by the loads it imparts to the hub and nacelle models. The rotor mass increases with its diameter, but so do the aerodynamic loads that are then transferred to the hub and nacelle. The hub, pitch system, low-speed shaft, main bearings, and bedplate are affected by rotor weight and thrust and the semi-empirical models resize them according to those inputs. The tower in this model is unaffected because this would require a suboptimization that is beyond the current scope. The new turbine cost model directly relates component sizes to costs; therefore, the resizing of the rotor and nacelle components leads to a proportional change in TCC. Rotor diameter also has a strong relationship to AEP because the power curve is adjusted, using the new RotorSE code, to capture more energy and reach rated power at lower wind speeds. The overall effect is that COE is negatively correlated to rotor diameter. However, this correlation does not consider how resizing the rotor blade without changing the rest of its design will impact rotor performance.

There is still little dependency in the model on maximum tip speed, though it does now have a relationship to AEP as it begins to constrain the turbine performance at relatively unrealistic values of below 60 m/s. There is also a minor effect of extreme tip speed constraints reducing aerodynamic loads, thereby reducing hub and nacelle masses and costs for an overall TCC reduction, but this again is only in the under 60 m/s range. Generally, maximum allowable tip speed continues to have little influence on COE and this demonstrates, once more, the need for

reoptimization of various parts of the system to truly understand the design dependencies. The same can be said of hub height, which has some impact on TCC through the change in tower mass, and on AEP because of the wind shear effects. Just as with the rotor, changing the tower height without changing other aspects of the tower design is expected to affect the structural integrity of the tower under various load cases. These performance factors are an indication of the types of suboptimization necessary for detailed study of the impacts of turbine configuration parameters on system performance and cost. The following scatter plots show the sensitivity study impacts of the key turbine configuration parameters on rotor and tower design margins. Design margins must be greater than zero to avoid system failure.



**Figure 8. Scatter plots and curve fits for the WISDEM global sensitivity analysis performance variables.** Variables have been normalized against reference values as described in Section III.B, except for performance margins that are reported in absolute values. The curve fit  $R^2$  values are provided above (denoted as  $R$ ). The performance variables are shown in the figure from top to bottom: tower Von Mises stress margins (s.m.) at the monopile base (sea floor) and monopile/tower interface, tower buckling margins (b.m.) at the same locations, and blade axial (maximum compressive) stress margin (a.m.) along the blade.

Here in the performance variable sensitivities, the limitations for not allowing subsystem redesign surface. For the tower, a clear negative correlation between hub height and the design stress margins can be seen. For this study, design margins for Von Mises stress to combine the three-dimensional stresses into an equivalent stress on the upwind side of the tower and shell buckling are used to evaluate the sensitivity of the tower structural performance to the input parameters. The design margins for the von Mises stress and shell buckling decrease as the rotor diameter, rated power, and hub height increase. This can be seen from the scatter plots as well as the correlation statistics shown in Table 8. The strongest correlation for the tower design margins is to hub height, as expected, but there are also significant correlations to rotor diameter and rated power. Increasing either rotor diameter or rated power will increase the overall mass of the RNA. As rotor diameter increases, so does blade size and mass. Further, the loads transferred to the hub and nacelle increase, thereby leading to larger sizing of the main load bearing components including the hub, pitch bearings, low-speed shaft and main bearings, gearbox, and bedplate. So, the overall mass increases and the loads on the tower increase because of the RNA weight. A similar, though less pronounced effect, takes place when the rated power increases, which affects the sizing of the generator and increases the overall gearbox ratio, leading to a larger gearbox and overall RNA mass. Both of these resizing effects in the hub and nacelle systems are caused by the use of the semi-empirical model for these systems rather than the true physics-based models. Thus, the simplified model can be quite useful for analysis if a researcher wants to



integrate optimization of the rotor and tower without having to account for all of the detailed aspects of the hub and drivetrain system design.

The resizing of the hub and drivetrain is not ideal for this study because it introduces automatic sizing to one part of the system whereas the rest of the system design (except for input parameters) remains fixed. Still, there are effects from changing the rotor diameter and rated power that are valid. In particular, as the rotor diameter and rated power increase, there is an increase in the maximum thrust loads transferred from the rotor to the rest of the system, which impacts the tower performance. The loads from the rotor increase most significantly with rotor diameter, as compared to rated power, and are expected to increase with hub height because of the effects of wind shear at the site (in this case small because the shear exponent itself is only 0.1). Increasing the maximum allowable tip speed would be expected to have some effect on the loads, and thus RNA mass and tower performance, though there is little evidence of this in the scatter plot and the correlation coefficients are quite low. Table 8 shows strong negative correlations for tower design margins with respect to hub height, moderate for rotor diameter, and low for rated power.

**Table 8. Correlation Coefficients across Inputs and Performance Outputs for the Sensitivity Analysis using New WISDEM Models.**

	rotor diameter	rated power	hub height	maximum tip speed	monopile base s.m.	tower base s.m.	monopile base b.m.	tower base b.m.	blade min a.m.
monopile base s.m.	-0.58	-0.21	-0.87	-0.10	1.00				
tower base s.m.	-0.58	-0.21	-0.87	-0.09	1.00	1.00			
monopile base b.m.	-0.57	-0.22	-0.83	-0.08	0.99	0.99	1.00		
tower base b.m.	-0.57	-0.22	-0.81	-0.08	0.98	0.99	1.00	1.00	
blade min a.m.	-0.97	-0.02	-0.33	0.02	0.60	0.60	0.60	0.60	1.00

For the maximum compressive stress margin along the blade (which occurs about three-quarters of the way along the length of the blade), there are strong correlations to the rotor diameter as expected, as well as the hub height through the previously mentioned effect of increasing design wind speeds with the site wind shear profile. There is little impact of rated power and maximum tip speed. It is typically expected that changing the maximum allowable tip speed would impact the rotor aerodynamic loads, but in this case, we are looking at the blade loads under extreme parked wind speed conditions only and are neglecting operating loads. Here, the loads on the blade that are used to calculate the maximum compressive stress come from the IEC 61400-1 edition 3 Design Load Case 6.1 for the Extreme Wind Speed Model with a reoccurrence of 50 years.<sup>33</sup> For the NREL 5-MW wind turbine, that is a class IB turbine, and the extreme wind speed  $V_{e50}$  is given by:

$$V_{e50} = 1.4V_{ref} \left( \frac{z}{z_{hub}} \right)^{0.11} \quad (4)$$

Where  $V_{ref}$  is the reference wind speed for the wind class, in this case 50 m/s for class IB, for a height  $z$  relative to  $z_{hub}$ . Thus, because the class of the turbine is fixed for the analysis, the maximum compressive stress on the blade is affected mainly by the rotor diameter and hub height, as the hub height decreases substantially below its reference value. To get a better picture of the interactive effect between hub height and rotor diameter on the blade axial / maximum compressive stress margin, we can also look at the Sobol indices.

**Table 9. Sobol Indices for Inputs on Turbine Performance Response of the WISDEM Model Set**

	Monopile Base S.M.		Tower Base S.M.		Monopile Base B.M.		Tower Base S.M.		Blade Min A.M.	
	Main Effect	Total Effect	Main Effect	Total Effect	Main Effect	Total Effect	Main Effect	Total Effect	Main Effect	Total Effect
rotor diameter	0.07	0.14	0.09	0.15	0.28	0.34	0.17	0.22	0.39	0.73
rated power	0.02	0.07	0.02	0.07	0.02	0.11	0.03	0.11	0.00	0.00
hub height	0.80	0.87	0.79	0.85	0.57	0.66	0.70	0.75	0.28	0.52
maximum tip speed	0.00	0.07	0.00	0.07	0.00	0.09	0.00	0.09	0.01	0.03

For axial stress margins, rotor diameter has a substantial main effect. When the interaction effects of the rotor diameter are included with the other variables, predominantly hub height, most of the variance in the axial stress margin is explained. For the tower, the hub height dominates as expected, though there is a significant contribution

from the rotor diameter as well. However, unlike with the stresses on the blade, the interaction between the contribution from hub height and rotor diameter is more limited and most of the variance is caused by changing hub height alone. The Sobol indices for the cost side of the analysis also show some interesting results.

**Table 10. Sobol Indices for Inputs on System Cost and Performance Response of the WISDEM Model Set**

	COE		AEP		BOS		OPEX		TCC		Turbine Mass	
	Main Effect	Total Effect	Main Effect	Total Effect	Main Effect	Total Effect	Main Effect	Total Effect	Main Effect	Total Effect	Main Effect	Total Effect
rotor diameter	0.54	0.66	0.65	0.76	0.09	0.22	0.09	0.39	0.20	0.62	0.13	0.65
rated power	0.06	0.08	0.03	0.13	0.75	0.92	0.49	0.62	0.15	0.24	0.02	0.09
hub height	0.01	0.04	0.00	0.09	0.01	0.13	0.05	0.23	0.07	0.29	0.19	0.47
maximum tip speed	0.26	0.35	0.13	0.16	0.00	0.02	0.03	0.25	0.07	0.45	0.06	0.41

In this study, there are many interactions revealed in the components that make up overall system COE. Specifically, there are pronounced interactive effects for TCC as well as OPEX. Given the number of interactive effects mentioned earlier with respect to simultaneous changes of the four input parameters on sizing of the hub and nacelle system, it is not surprising to see the significant increase between the main and total effects for all of these parameters. Furthermore, the interactive effects on TCC impact OPEX, which is primarily affected by overall turbine capital costs in the current version of the model.

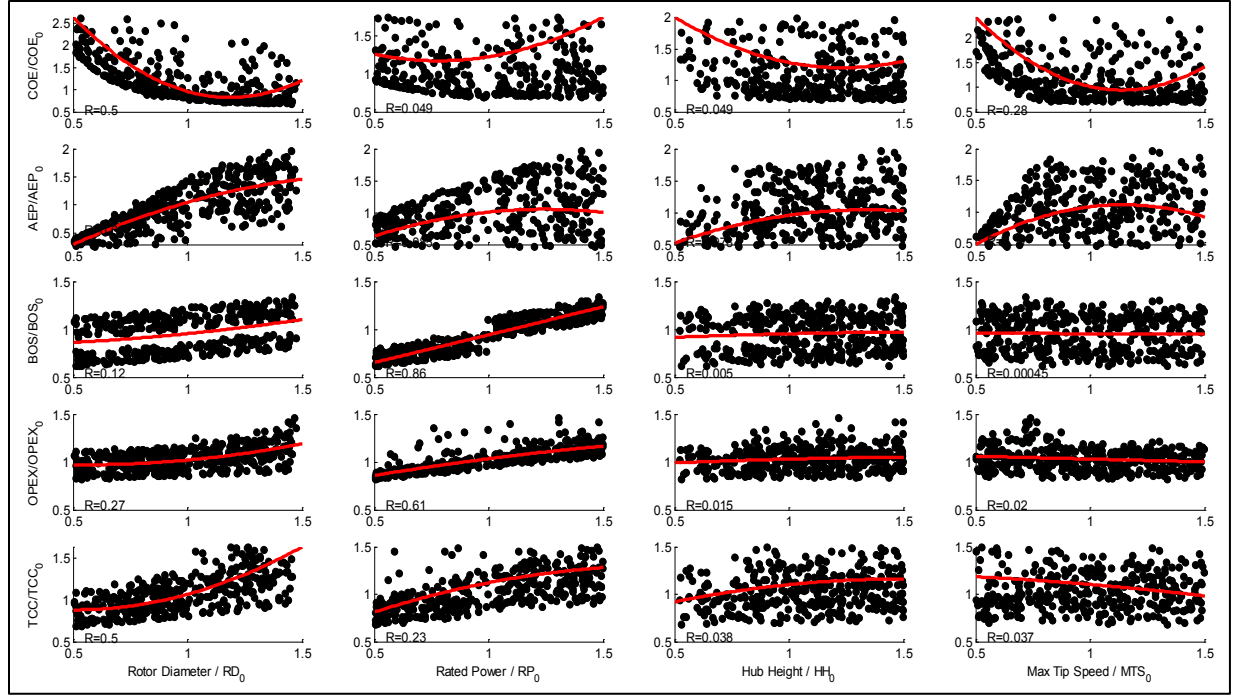
Such an impact of the input parameters through both main and total effects is expected, though not for the reason mentioned above. As previously mentioned, failure rates in the OPEX model are kept constant at present, and are based on empirical data from the industry. As the results for the rotor axial stress and tower design margins indicate, without turbine redesign, the failure rates for at least these subsystems would be affected by varying the input parameters over the ranges in this study. For the scope of this study, it is not possible to reasonably update the failure parameters. A more realistic model set would also permit an assessment of design changes on reliability and operations.

For overall energy production and cost, the primary effect comes from the rotor diameter with some interaction from maximum tip speed and rated power in particular. In this case, rotor diameter has a strong influence over energy production and consequently, overall system costs. For a particular plant with a prescribed layout, the effect of rotor diameter on energy production would not be as straightforward. This set of models uses plant energy losses as an input, specifically because of array effects from turbine flow interactions. As the rotor diameter and other parameters change, the losses, as with the rest of the plant input variables, are kept constant. In the last model set configuration, researchers included a model for plant energy production with built-in wake modules to capture effects related to plant losses.

### 3. WISDEM with OpenWind

In this final model set, we substituted a plant layout tool that includes a wake model in the analysis of plant energy production. This study uses AWS Truepower OpenWind, though other similar models could be used if coupled to the system model. The enterprise version of OpenWind contains several capabilities including a deep array wake model specifically designed for offshore plants and BOS costs with special emphasis on costs for electrical array cabling. Here, we are using the NREL offshore BOS model, so only the energy production functionality of OpenWind is used.

The enterprise version of the model has been designed with a scripting capability so that the turbine definition may be controlled externally to the software as part of a larger analysis process. It also offers the ability to optimize the layout through external scripting, but this would require a redesign of the plant, and similar to the rotor and tower, we are treating everything as constant in this analysis except for the four key turbine configuration parameters of interest to the study. The OpenWind model replaces the NREL CSM annual energy production analysis. That analysis used the turbine power curve convolved with the site Weibull distribution multiplied by the number of turbines multiplied by the turbine and array losses. Thus, researchers fixed the array losses and did not consider the effect of turbine flow interaction. In this final analysis, we included the wake effects through the inclusion of OpenWind. It should be noted, however, that with the current version of OpenWind, adjusting the hub height *in situ* during an analysis was not possible, and so the relationship with hub height and AEP was not captured. Below are the new results repeating the WISDEM analysis and replacing the AEP analysis of NREL CSM with OpenWind.



**Figure 9. Scatter plots and curve fits for the WISDEM with OpenWind global sensitivity analysis.** *Input and output variables have been normalized against the reference values as described in Section III.B. The curve fit  $R^2$  values are provided above (denoted as  $R$ ).*

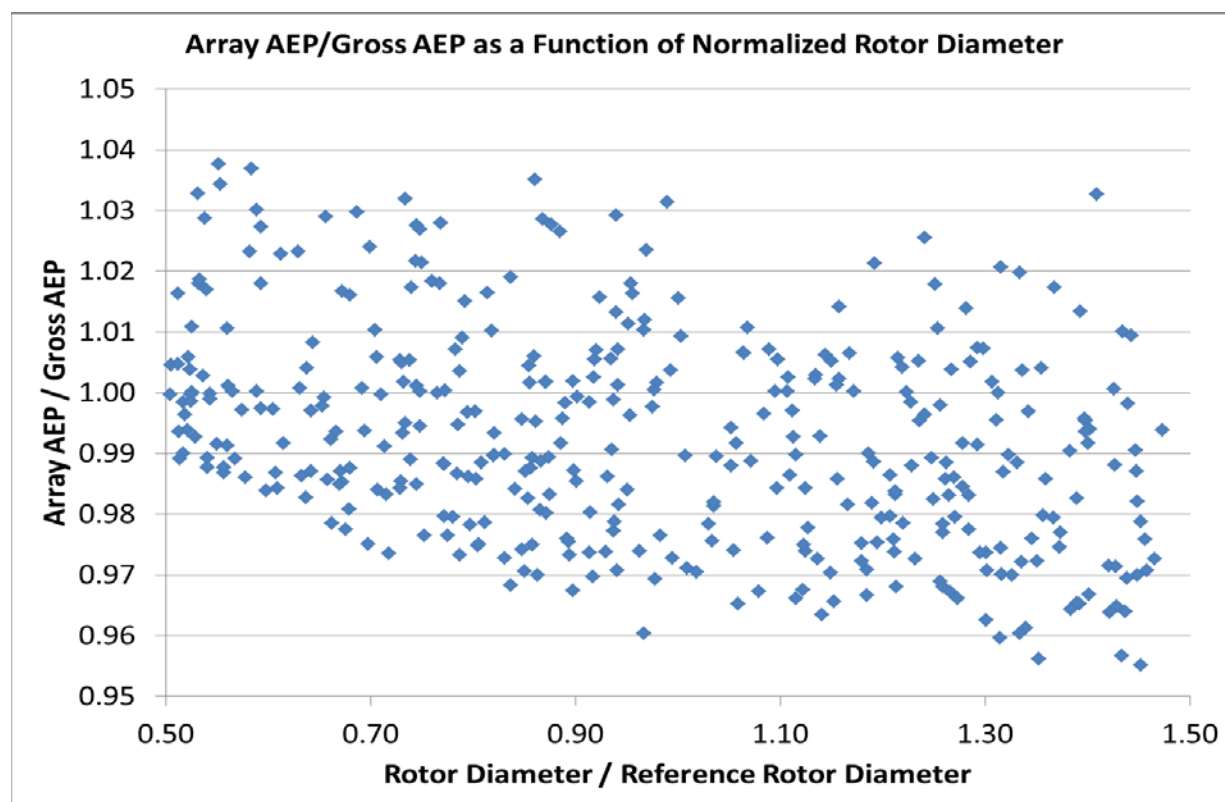
The differences caused by the inclusion of turbine interaction effects on energy production are minimal. The relationships of the input variables to TCC, OPEX, and BOS are consistent with the prior analysis, as expected, because only the energy production analysis has changed. As anticipated, there is no modeled relationship of hub height to AEP and there is some relationship with maximum tip speed. A positive relationship appears between AEP and rated power as well as rotor diameter as would be expected. The improved relationship between rated power and AEP is still not strong enough to compensate for the strong BOS dependency, and there is still a positive correlation of rated power to COE.

For rotor diameter, we see that the energy production is still positively correlated with AEP though with a less strong correlation than in the prior case. This result is because the turbines are spaced close enough within the layout that the wake effects are affecting the relationship of rotor diameter to energy production. The increased blockage of downstream turbines by larger diameter rotors within the fixed layout counteracts the increased energy production potential of the larger rotors. Still the overall correlation of rotor diameter with COE is negative since even with the additional effect of wake losses, because the gross energy production is so strongly correlated with rotor diameter. The wake losses for the reference plant are 6% and reach a maximum of 10% for very large rotor diameters. For similarly large rotor diameters, gross energy output will increase by up to two times the reference plant energy output. The correlation coefficients support these results, as shown in Table 11.

**Table 11. Correlation Coefficients across Inputs and Outputs for the WISDEM Sensitivity Analysis**

	rotor diameter	rated power	hub height	maximum tip speed	COE	AEP	BOS	OPEX	TCC	turbine mass
COE	-0.62	0.18	-0.02	-0.37	1.00					
AEP	0.76	0.23	0.14	0.29	-0.76	1.00				
BOS	0.35	0.84	0.00	-0.02	-0.05	0.51	1.00			
OPEX	0.40	0.71	0.17	-0.13	-0.09	0.53	0.86	1.00		
TCC	0.55	0.43	0.24	-0.17	-0.24	0.59	0.64	0.92	1.00	
turbine mass	0.49	0.22	0.39	-0.17	-0.26	0.53	0.41	0.78	0.94	1.00

If the turbines were initially placed far away from each other, then the outcome would be expected to be different. Still, the use of the deep array wake model, which can carry the wake 10 or more turbine diameters downstream<sup>34</sup>, allows the wake effects to feature prominently even when the turbines are spaced relatively far apart. This is further illustrated in Fig. 10, which shows how array AEP relative to gross AEP changes with rotor diameter.



**Figure 10. OpenWind array AEP/gross AEP output as a function of normalized changes in rotor diameter. Array AEP represents the deviation from gross AEP caused by turbine-wake interactions.**

In addition, the further the turbines are apart, the higher the costs will be for the electrical array cable system. If the plant layout were to change during the analysis, these costs would be important to the overall sensitivity. Although the analysis above exposes the limitations in the analysis setup—where plant layout is fixed but gross turbine features are changing—it highlights the need to account for complex flow in the overall system cost modeling. As the turbine changes, it shouldn't be assumed that the array losses are a fixed input. The results also highlight the benefit of joint turbine and plant optimization as a result of the complex relationships that exist between turbine configuration and plant energy production.

#### 4. Comparison

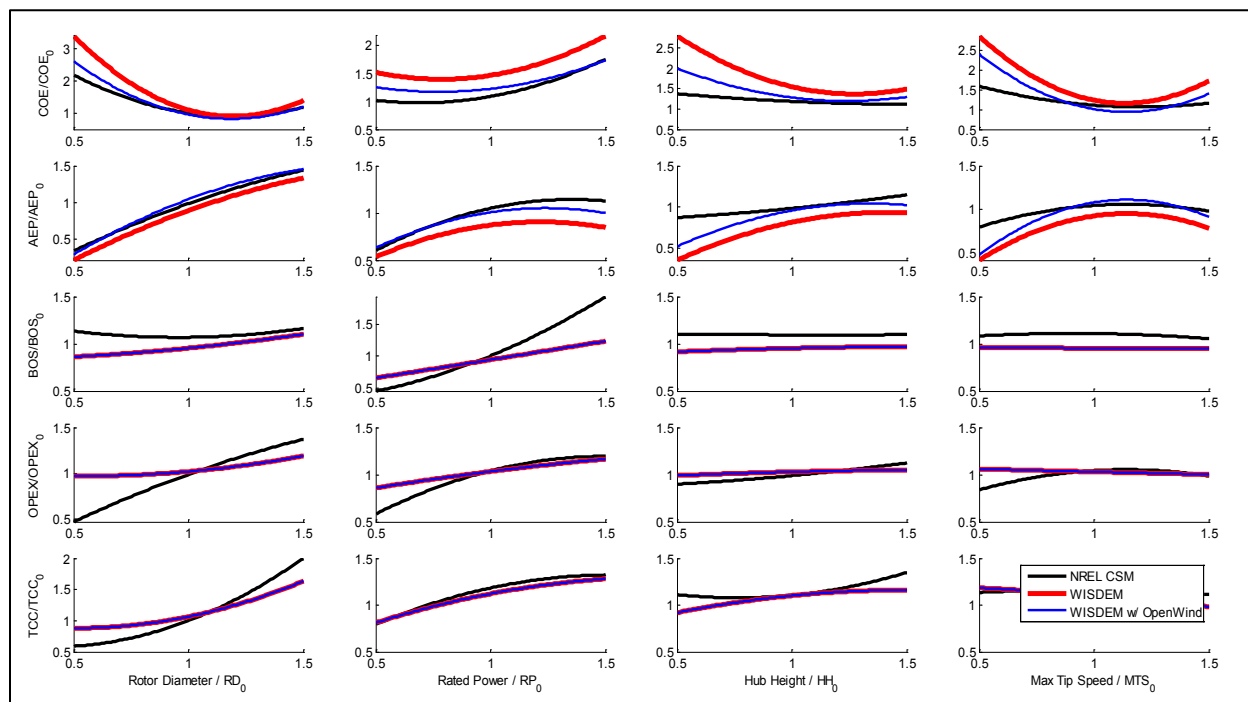
Looking across the three studies, the utility and limitations of each are apparent. The NREL CSM is essentially a parametric model (sometimes referred to as a meta-model or surrogate model) for a series of detailed design studies which abstracts the results into a simple set of parametric relationships based on a small number of variables. Researchers used simple regression analysis to define relationships between various output parameters and a small set of important system input parameters with emphasis on the turbine configuration parameters of rotor diameter, rated power, hub height, and maximum tip speed. However, use of such an abstract model can be constraining if it is not constructed properly or if the underlying designs are substantially changed. In this study, both of these limitations affected the NREL CSM results. First, the initial relationships oversimplified the underlying relationships and often reduced the dependencies to single input-output relationships. This means that many important system interactions were lost. From the turbine perspective, although the model was useful for exploring system relationships to rotor diameter and rated power, relationships with other turbine design parameters were absent or deemphasized. Also, since the initial model development was built on work from the previous decade, the

technology that the model represents is no longer an accurate representation of current wind turbine technology and trends.

Thus, efforts were taken to improve upon the NREL CSM for the turbine component sizing and cost models. For the rotor and tower, however, new physics-based models have been developed. All of these models replaced the turbine model in the creation of the new WISDEM TurbineSE model set. The result is that various interactions with these models are now present. This is evident in the Sobol indices for turbine mass and cost resulting from the global sensitivity analysis of the model set. The difference between the rotor and tower models to the hub and nacelle models were highlighted: the rotor and tower models will not resize properly without optimization whereas the hub and nacelle models are still semi-empirical sizing tools. For a study dedicated specifically to rotor and tower optimization, the automatic sizing of the hub and nacelle is useful, though the validity of the sizing relationships in these models is hampered by the same limitations as in NREL CSM. In any given study, it is useful to have higher fidelity models for the particular features of the system under study and more automated models for those that are less critical to the particular analysis or design focus.

In addition to the new TurbineSE and Turbine\_CostsSE models, new Plant\_CostsSE models were used as part of the WISDEM analysis. Although these models are a strong improvement on NREL CSM because of their calibration and extensive use of industry data, they are still limited from a system analysis perspective in terms of the interactions to other parts of the system. The strong dependence of BOS on rated power is a primary example, whereas for OPEX, the lack of ability to tie design margins to component failure rates makes OPEX overall relatively insensitive to turbine design changes.

Finally, the incorporation of OpenWind accounts for the effects of turbine interactions on plant energy production. The use of such a model, which is also computationally expensive, may be unnecessary for many turbine-specific analyses, but it is important for understanding the interaction between turbine design and plant design—including layout and the effect that the layout and turbine selection will have on AEP and BOS. There is evidence from this study that improved coupling of turbine and plant models, even as simple as those used in this study, may enable joint turbine and plant optimization that will further improve system performance and reduce overall COE. This is further illustrated by superimposing the curve fits for each of the three cases on single plots as shown in Fig. 11. However, care should be exercised in using simplified wake models. If the plant interaction model is too simple, or inaccurately reflects more complex physics of turbine interaction, it could drive optimization in the wrong direction.



**Figure 11. Reference curves for input-output sensitivities for each of the three model set configurations.**

For each of the four input parameters, the WISDEM model configuration shows the largest range and strongest nonlinearity in COE response to changes in inputs. The sensitivity results are identical between the WISDEM and WISDEM with OpenWind cases except for AEP and thus overall COE. This is due to the turbine wake interaction effects that were discussed previously. Between NREL CSM and WISDEM, there is a similar strength in the relationship between the input parameters and AEP. Unlike the NREL CSM, however, an actual aerodynamics model is used in WISDEM to develop the turbine power curve such that it is more sensitive to maximum tip speed and hub height. Still, the moderate correlation values and small  $R^2$  values for those relationships indicate that the influence should be interpreted with caution. BOS is very sensitive to rated power and relatively insensitive to other variables regardless of the model set and indicates a significant limitation of the models that should be addressed in future model development. OPEX is very sensitive to rated power and rotor diameter for the NREL CSM since it is entirely dependent on AEP as mentioned before. The sensitivity is largely reduced for the WISDEM cases since the new OPEX model is affected slightly by TCC and not much else – failure rates being model inputs which are not updated. Updating failure rates is important to linking turbine design to component replacement costs but the current set of models does not have this capability. TCC is sensitive to all input parameters save maximum tip speed though there is a reduction of sensitivity in the WISDEM case since there is no re-design of the tower and rotor. Finally, the COE sensitivities are strongest for WISDEM with and without OpenWind over NREL CSM. Certainly, more elastic sensitivities are developed moving NREL CSM to WISDEM though significant limitations are still present.

#### IV. Conclusions

This study demonstrated capabilities and limitations of a new integrated wind plant system modeling tool, WISDEM, by using the system tool to create three different model configurations and analyzing each of them using a global sensitivity analysis of key turbine configuration parameters on wind plant system performance and overall COE. The results of the correlation of COE to turbine configuration parameters of rotor diameter, rated power, hub height, and maximum tip speed for each model set are summarized in a side-by-side comparison in Table 12.

**Table 12. Side-by-Side Comparison of Correlation Coefficients of Input Variables to COE for Each Study**

	NREL CSM COE	WISDEM COE	WISDEM w/ OpenWind COE
Rotor Diameter	<b>-0.50</b>	<b>-0.66</b>	<b>-0.62</b>
Rated Power	<b>0.42</b>	<b>0.20</b>	<b>0.18</b>
Hub Height	<b>-0.14</b>	<b>-0.27</b>	<b>-0.02</b>
Maximum Tip Speed	<b>-0.24</b>	<b>-0.35</b>	<b>-0.37</b>

The limitations of each model set for system analysis were discussed. While the NREL CSM provides simple scaling relationships, which can be useful either as a full system study or to represent a part of the system coupled to models in another study, this meta-model is limited by the level of oversimplification and by the outdated technology design data that was used in its construction. There is an overly strong relationship between rotor diameter and rated power to overall COE and the validity of the correlations for each could be suspect. The model was originally designed using curve fits primarily on rotor diameter and rated power to turbine component sizes and costs as well as plant costs. The new WISDEM offers new turbine models that provide physics-based analysis of the rotor and the tower and replaces the dependencies of turbine component cost on rotor diameter with dependencies tied to individual component sizes. However, the rotor and tower models require an internal optimization loop to be truly useful in a design study, which introduces complexity and the need for care in choosing the independent variables and constraints for each model (as well as objectives in the case of suboptimization). Still, overall interactions in the system noticeably increased and there is improved accounting for other turbine design variables like hub height and maximum tip speed.

The third study using OpenWind showed that it is important not to neglect aspects of turbine interaction in the plant in terms of understanding energy production. The model setup with a fixed layout results in the finding that increased rotor diameter will increase energy production but wake losses will increase such that the array AEP relative to gross AEP will decrease. This result in AEP output shows that wake effects produce a significant sensitivity of the joint turbine-plant design to energy production. In turn, this can be extended to not just energy production but, for more complex dynamic models, also turbine loads, component performance, and operations expense. This study points to the utility of integrated system modeling in exposing and capturing various system



interdependencies and highlights the challenges that exist in analysis design for integrated modeling in order to properly target the design objective or research question.

## V. Future Work and Model Development

The new WISDEM modeling capability for wind plants can be flexibly adapted to integrate models of various levels of fidelity into subsystem and overall system models. The potential variety of studies that could be performed using the new capability is endless and allows individual users to fine-tune their model selection and analysis setup to target their exact research questions of interest. As the tool develops, new models are planned to increase fidelity both at the turbine and plant levels, and users will have a variety of options at their disposal to represent each subsystem of the plant. A user looking at a new innovation and redesign of the turbine may use simple models to represent plant costs and energy production while using high-fidelity models to represent certain turbine components in particular. This might be the case, for example, where the research question focuses on innovative rotor design and simple sizing models are useful for the drivetrain and tower. Another more focused study on the drivetrain may benefit from simplified models of the rotor and tower. On the other hand, someone looking at detailed design of a plant may use a very simple turbine model – even as simple as the one represented by the NREL CSM. Lastly, users may choose to have models of intermediate to high fidelity representing both the turbine and the plant to perform joint turbine-plant optimization studies. It is expected that meta-modeling, which has been used in previous wind turbine optimization studies, will be particularly important for joint turbine-plant optimization.

Regardless, much work still exists to develop the model set to provide a more realistic representation of system interdependencies. A primary example is the OPEX model where there is a need to represent how changes in turbine design affect failure rates and repair and replacement costs. Other cost models for the turbine and BOS also would benefit from development in terms of detail and dependencies to better support understanding of design changes on overall system costs. Complementing the higher fidelity models, a set of meta-models that reduce the complexity (and computational requirements) of all the models will be necessary for enabling detailed studies of certain parts of the system that still capture important system interactions. As new models are developed, additional studies will be carried out to build and improve understanding of how innovations, design changes, and uncertainties affect overall wind plant system performance and cost.

## Acknowledgments

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